ARMY RESEARCH LABORATORY

Determination of the Similarity Theory Scaling Parameters from the Vertical Gradients

by Frank V. Hansen
Henry Rachele
Arnold Tunick
Battlefield Environment Directorate

ARL-TR-286

June 1994

Approved for public release; distribution is unlimited.

NOTICES

Disclaimers

Destruction Notice

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 1994	Final

4. TITLE AND SUBTITLE

Determination of the Similarity Theory Scaling Parameters from the Vertical Gradients

5. FUNDING NUMBERS

6. AUTHOR(S)

Frank V. Hansen, Henry Rachele, and Arnold Tunick

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Research Laboratory
Battlefield Environment Directorate
AMSRL-BE-S
White Sands Missile Range, NM 88002-5501

8. PERFORMING ORGANIZATION REPORT NUMBER

ARL-TR-286

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Research Laboratory
2800 Powder Mill Road
Adelphi, MD 20783-1145

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

ARL-TR-286

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

A

13. ABSTRACT *(Maximum 200 words)*

Dynamic similarity of flows theory as applied to the surface boundary layer of the atmosphere must be treated as an interwoven quardrapartite function of trivariant orthoginal turbulent motion, the thermal structure and associated vertical gradients, evaporation at the interface, and vertical transport of water vapor with respect to the specific humidity as a function of height. Physical studies of the surface layer are typically conducted with respect to the buoyant heat flux and the momentum flux. Buoyancy is associated with the sensible and latent heat fluxes. The key parameters for establishing the vertical fluxes are the scaling velocity, scaling temperature, and scaling humidity. An interpretation of the similarity theory developed from the basics of the mean value theorem of calculus allows evaluation of the scaling parameters without utilizing the mathematically complex diabatic influence functions, but directly from the vertical gradients of wind, temperature, and specific humidity.

14. SUBJECT TERMS	15. NUMBER OF PAGES
micrometerology, Obulchov similarity, flux-profile theory	29
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

Contents

Figures

1. Introduction

Surface boundary layer processes, in particular the turbulent kinetic energy budget and the surface energy balance, are cohesively linked to the vertical profiles of wind, temperature, and specific humidity that characterize the mean flow and turbulent structure of approximately the first 100 m of the atmosphere. The shapes of the vertical profiles are deemed to be controlled by the nondimensional parameters of the dynamic similarity theory of Obukhov. [1] Priestley [2] suggested that the Richardson [3] number was the sole controlling parameter of similarity near the earth's surface. Two significant entities that have a profound effect on dynamic similarity and the surface energy balance must be added to Priestley's corollary, the aerodynamic roughness length, and the latent heat flux via local evapotranspiration rates. Surface roughness length has significant effects on vertical wind shear; larger shears are associated with larger values of surface roughness. Large wind shears and increases in the vertical latent heat flux caused by increased evapotranspiration have a stabilizing effect on the atmosphere. The addition of water vapor to the atmosphere reduces the sensible heat flux, which leads to the stabilizing phenomenon.

An orderly and comprehensive examination of the surface energy balance requires detailed analyses of the vertical profiles of wind, temperature, and humidity with respect to atmospheric stability. Application of dynamic similarity principles to the micrometeorological characteristics of the surface boundary layer is interwoven with the nature of turbulent flow in which the instantaneous orthoginal velocities exhibit irregular, random fluctuations so that only the statistical properties can be subjected to analyses. Thus, profile analysis is generally based on averages formed over some arbitrary time interval and at preselected measurement levels on an instrumented tower or mast. Analytical arguments concerning the best approaches to defining the profiles are undertaken.

2. Buoyancy in the Surface Layer

Buoyancy is an atmospheric property of an air parcel that allows it to ascend and remain suspended in a compressible fluid such as the atmosphere. In the atmosphere, a buoyant force on a parcel of air may be directly attributed to a local increase in temperature resulting from the heating of the atmosphere at the air-earth interface by conduction, which immediately leads to a vertical energy transfer by convection. The work done by buoyancy against gravity results in a decrease with height of potential temperature, a characteristic of an unstable atmosphere.

Conversely, during the nocturnal hours, in the absence of incoming solar energy, the kinetic energy of the turbulent fluctuations will decrease, because of the extraction of energy from the mean motion by the Reynolds stresses. The atmosphere becomes quiescent and the mean flow approaches laminar flow conditions. The atmosphere is said to be stable.

The stability of the atmosphere may be expressed as the ratio of mechanical production to the convective production of energy. This ratio is generally known as the gradient form of the Richardson [3] number or the Obukhov [1] scaling length. Richardson, in the development of his criterion of turbulence, did not fully consider the effects of water vapor on atmospheric stability. Obukhov also omitted this important detail in his arguments leading to the dynamic similarity of flows theory. Lumley and Panofsky [4] discussed the importance of water vapor to the dynamics of the atmosphere. Busch [5] redefined the Obukhov length L with respect to the affect of water vapor and the latent heat flux on atmospheric stability as

$$L = - \frac{u_*^3 c_p \rho \theta}{kg(H + 0.07 \mathcal{L} E)} = \frac{u_*^2 \bar{\theta}_v}{kg\theta^*} \qquad (1)$$

where

u_*	=	a scaling or friction velocity
c_p	=	the specific heat of air at constant pressure
ρ	=	density

k	=	Karman's constant
g	=	gravitational acceleration
H	=	vertical sensible heat flux
$\mathcal{L}$	=	latent heat of vaporization
E	=	evaporation rate
$\mathcal{L}$ E	=	latent heat flux
$\bar{\theta}$	=	mean potential temperature
$\bar{\theta}_v$	=	virtual potential temperature
θ^*	=	virtual scaling temperature.

By definition, the scaling length L is related to the gradient Richardson number, R_i, by

$$\frac{z}{L} = R_i \, \phi_M \, \frac{K_H}{K_M} = R_i \, \frac{\phi_M^2}{\phi_H} . \tag{2}$$

where

z/L	=	Monin and Obukhov [6] scaling ratio
K_H	=	exchange coefficient for heat
K_M	=	exchange coefficient for momentum
ϕ_M	=	dimensionless lapse rate.

Based on the O'KEYPS* function, it may be demonstrated that in unstable flow $z/L = R_i$, because $\phi_H = \phi_M^2$, and in a thermally stratified stable regime, $z/L = R_i \, \phi_H$, because $\phi_H = \phi_M$. Therefore, in an unstable regime,

$$\frac{z}{L} = R_i = \frac{g \Delta \theta_v}{\bar{\theta}_v (\Delta \bar{v})^2} \, z_g \, \Delta \ln Z \tag{3}$$

**O'KEYPS is an acronym formulated by Panofsky [7] and Yaglom [8] and recognizes the major contributors to the development of contemporary dynamic similarity theory Obukhov, [1] Kazanski and Monin, [9] Ellison, [10] Yamamoto, [11] Panofsky, [12] and Sellers. [13]*

where

$\bar{v}$ = mean horizontal wind speed
z_g = geometric mean height of the layer $z_2 - z_1$.

For stable mean flow conditions, Hansen [14] found that $\phi_M = (1 + 15\ R_i)$, allowing z/L to be expressed as

$$\frac{z}{L} = R_i\ (1 + 15\ R_i). \tag{4}$$

The use of virtual potential temperature for surface boundary layer physical processes is basic to proper and accurate solutions. Virtual potential temperature is the temperature necessary for dry air to produce the actual density at ambient pressures, expressed as

$$\bar{\theta}_v = \frac{\bar{\theta}}{1 - 0.379\ e/p} \tag{5}$$

or

$$\bar{\theta}_v = \bar{\theta}(1 + 0.61\ \bar{q}) \tag{6}$$

where

e = partial pressure of water vapor
p = atmospheric pressure
$\bar{q}$ = mean specific humidity.

3. The Mechanics of Vertical Profiles

Investigation and examination of surface boundary layer phenomena usually involve the collection of representative experimental data. In the interest of economy, not only in collecting experimental data, but also in processing samples, vertical profiles are usually observed. This means data are analyzed using bulk aerodynamic methods.

Traditionally, the instrumentation of towers and masts has been at heights above the surface established by application of the law of natural growth. This results in measurements at instrument levels spaced in a geometric or logarithmic progression. It also suggests that the vertical gradients are tangent to the profiles at the geometric mean height of each layer. Rachele, Tunick, and Hansen [15] investigated the validity of this premise via the mean value theorem of calculus; finding that the true point of tangency was not at the geometric mean height of a layer, but 8.2 percent above $zg = (z_1 \cdot z_1)^{1/2}$. Equation (3) for R_i is now written as

$$R_i = \frac{g}{\bar{\theta}} \frac{\Delta\bar{\theta}_v}{(\Delta v)^2} \Delta z \tag{7}$$

because, from the mean value theorem,

$$z = \frac{\Delta z}{\Delta \ln z}. \tag{8}$$

This is only of academic interest because values of R_i calculated for heights of zg or z translate into identical values of L. The important point is that data analysis, using either the law of natural growth or the mean value theorem, yields cogent estimates of atmospheric stability.

The stochastic nature of turbulent flow implies that statistical methods must be invoked to temporarily smooth the data for each tower or mast level. Customarily, the Richardson numbers or Monin-Obukhov scaling ratios are formed at this point in the analysis. An inspection of the stability parameters usually reveals a nonuniform distribution with height, and on conversion to Obukhov lengths, a variable L with height. Dynamic similarity requires a constant scaling length throughout the surface layer. The variability of L with height can be attributed to production and dissipation of mechanical and convective energy and eddies of several orders of magnitude in size impinging on or completely bypassing tower instrumentation. Irregular buoyancy and subsidence effects on anemometers or temperature and humidity sensors yield nonstationary appearing mean profile data.

Smoothing the profile heights can be accomplished in various ways. The simplest method is smoothing by eye (graphing the averaged data points as a function of height) and hand fitting a smooth curve to the points. Values picked from the curve are used to recalculate the stability parameters. A better fit can possibly be determined using a technique attributed to Businger et al. [16] For unstable flow conditions, differentiated second-order polynomials in lnz are fitted. For the stable regime, the polynomial a + blnz = cz was used. The smoothed values for each level of interest are used to evaluate the stability.

Additional smoothing of the stability parameters is required to provide best estimates of the Obukhov length. Lettau [17] introduced the concept of the approximate height derivative of the gradient Richardson number, that may be used as a smoothing technique, and is given by

$$L^{-1} = \frac{\Sigma(R_i)_z}{\Sigma(z)_i} \tag{9}$$

where

i = 1, 2, 3

which is valid for unstable conditions. For the stable regime

$$L^{-1} = \frac{\Sigma(z/L)}{\Sigma(z)} \tag{10}$$

after determining z/L from equation (4). This technique is referred to as a stationarity forcing function.

4. Dynamic Similarity in the Surface Layer

The O'KEYPS designation has been reserved to describe the functions associated with the linear-quartic profiles in unstable flow. We chose to use the acronym as an all-encompassing descriptor for both the unstable as well as the log-linear stable regime. The O'KEYPS originators, however, were not the sole contributors to the investigation of stable mean flow conditions in the surface boundary layer; there were many others, including Webb, [18] Oke, [19] and Hicks. [20]

During this investigation concerned with water vapor effects on stability, it soon became apparent that a number of simplifying shortcuts could be used in the data analyses. These abridged procedures were unique enough to deserve a separate moniker and were dubbed Mariah.* O'KEYPS and Mariah yield identical results, but Mariah requires much less computational effort.

The wind, temperature, and specific humidity profiles in the surface boundary layer of the atmosphere, written in differential form are

$$\frac{\partial \bar{V}}{\partial z} = \frac{u*}{kz}\,\phi_M \tag{11}$$

$$\frac{\partial \bar{\theta}}{\partial z} = \frac{T^*}{kz}\,\phi_H \tag{12}$$

**Mariah has no relationship to any meteorological phenomenon or individual, but was unabashedly lifted from the Broadway Musical and motion picture "Paint Your Wagon", in which Uncle Willie sang*

> *"....way out there they have a name for rain and wind and fire, the rain is Tess, the fire is Joe, and they call the wind Mariah."*

and

$$\frac{\partial \bar{q}}{\partial z} = \frac{q^*}{kz} \phi_w \tag{13}$$

where

T* = a scaling temperature associated with potential temperature
q* = a scalin, .umidity.

Within the framework of dynamic similarity, it is presumed that the transfer of heat and mass are identical, so $\phi_w = \phi_H$. From the O'KEYPS function, it is easily demonstrated that for unstable conditions

$$\phi_M = (1 - 15\ z/L)^{1/4} \tag{14}$$

and

$$\phi_w = \phi_H = (1 - 15\ z/L)^{1/2}. \tag{15}$$

Integrating equations (11), (12), and (13) using equations (14) and (15) yields

$$\bar{V} = \frac{u*}{k} \left[\ln z/z_o + \psi_M\ (z/L)\right] \tag{16}$$

$$\bar{\theta} - \theta_0 = \frac{T^*}{k} \left[\ln z/z_o + \psi_H(z/L)\right] \tag{17}$$

and

$$\bar{q} - q_0 = \frac{q^*}{k} \left[\ln z/z_o + \psi_M (z/L) \right]. \tag{18}$$

The diabatic influence functions are given by

$$\psi_M (z/L) = - \int_{z_o}^{z} \frac{1 - \phi_M}{z/L} \, d\,(z/L) \tag{19}$$

and

$$\psi_H (z/L) = - \int_{z_o}^{z} \frac{1 - \phi_M}{z/L} \, d\,(z/L) \tag{20}$$

and solved using Benoit's [21] method

$$\psi_M (z/L) = - \left\{ \ln \left[\frac{(\mathcal{L}_0^2 + 1) \, \mathcal{L}_O + 1)^2}{(\mathcal{L}^2 + 1) \, (\mathcal{L}_O + 1)^2} \right] + 2 \left[Tan^{-1} (\mathcal{L}) - Tan^{-1} (\mathcal{L}_o) \right] \right\} \tag{21}$$

where

$$\mathcal{L} \equiv \left[1 - 15 \, \frac{z}{L} \right]^{1/4}$$

$$\mathcal{L}_0 \equiv \left[1 - 15 \, \frac{z_0}{L} \right]^{1/4}$$

and

$$\psi_H\,(z/L) = 2\,\ln\left(\frac{\lambda_o + 1}{\lambda + 1}\right) \tag{22}$$

where

$$\lambda = \left[1 - 15\,\frac{z}{L}^{1/2}\right]$$

$$\lambda_0 = \left[1 - 15\,\frac{z_0}{L}\right].$$

The scaling temperature for unstable flow may be found from

$$T^{*} = \left(\frac{z}{L}\right)\frac{\theta\, u_*^2}{k\, z\, g} \tag{23}$$

and according to Myrup [22], q_o, the specific humidity at z_o, is determined from

$$q_0 = \frac{RH}{1000}\left[3.74 + 2.64\left(\frac{T_0}{10}\right)^2\right] \tag{24}$$

where

T_0 = the temperature at Z_0 in degree Celsius.

Equations (16), (18), and (23) now can be evaluated for u^*, q^*, and T^*, the initial scaling parameters required to solve the surface energy balance. This approach is laborious because it is necessary to first evaluate the diabatic influence functions in equations (21) and (22).

A second approach is to guess a value for the Obukhov length L (negative for unstable conditions and positive for stable). Using the value for L, a solution is found for equations (21) and (22). For known values of $\overline{V}$, θ, and q, u_*, T^*, and q^* are evaluated using equations (16), (17), and (18). The values are used to determine $H = - c_p \rho u_* T^*$ and $\mathcal{L}E = - \mathcal{L} \rho u^* q^*$ that are substituted in equation (1) to obtain a new estimate of L. This value of L is used to form new estimates of u^*, T^*, and q^*. The process is repeated until the scaling constants converge. The second approach is not very efficient, even with machine processing.

In a thermally stratified stable regime in which $z/L = R_i \phi_M$ and $\phi_H = \phi_M$, the integration of equations (11), (12), and (13) yields

$$\overline{V} = \frac{u*}{k} \left[\ln z/z_0 + \beta \frac{z}{L} \right] \tag{25}$$

$$\overline{\theta} - \theta_0 = \frac{T^*}{k} \left[\ln z/z_0 + \beta \frac{z}{L} \right] \tag{26}$$

and

$$\overline{q} - q_0 = \frac{q^*}{k} \left[\ln z/z_0 + \beta \frac{z}{L} \right] \tag{27}$$

where

β = a variable according to Hansen. [14]

If $\phi_M = 1 + \beta z/L$, then from equation (14)

$$\beta = \frac{15}{\phi_M} \tag{28}$$

where

$\phi_M = (1 + 15 R_i)$.

The scaling parameters may then be found from

$$u* = \frac{k \Delta\overline{V}}{\Delta \ln z + \beta \frac{\Delta z}{L}} \tag{29}$$

$$T^* = \frac{k \Delta\theta}{\Delta \ln z + \beta \frac{\Delta z}{L}} \tag{30}$$

and

$$q^* = \frac{k \Delta q}{\Delta \ln z + \beta \frac{\Delta z}{L}} \tag{31}$$

As with the unstable case, a value of L is needed to obtain values of u*, T^*, and q^* using equations (29), (30), and (31). This is done by employing an iterative approach similar to the unstable case.

5. The Mariah Approach

The Mariah approach evolved from a study by Hansen. [23] From the definition of the Obukhov [1] scaling length of equation (1), repeated here as

$$L = \frac{u_*^{H}\, \overline{\theta}_v}{kg\, \theta^*} \tag{32}$$

where

$$\theta^* = T^* + 0.61\ \theta q*, \tag{33}$$

we may substitute equations (11), (12), (13), and (32) in equation (1), yielding

$$L = \frac{\phi_H\, \overline{\theta}_v\, (\Delta V)^2}{g\, \Delta \ln z\, \phi_M^2\, (\Delta\theta + 0.61\ \theta\ \Delta q)}, \tag{34}$$

which is valid in both the stable and unstable regimes, and allows a direct calculation of L from the observed gradients. However, in stable conditions $\phi_H = \phi_M$; therefore, the denominator contains ϕ_M. Manipulation of equation (33) reveals that in stable flow

$$L = \frac{\overline{\theta}_v\, (\Delta V)^2}{g\, \Delta\, lnz\, (\Delta\theta + 0.61\ \theta\ \Delta q)} - 15\, \frac{\Delta z}{\phi_M\, lnz}, \tag{35}$$

which leads to

$$L = \frac{B^2}{60\ Z + 2B} \tag{36}$$

with z = $\Delta z/\Delta$ lnz, and

$$B = \frac{2\ \overline{\theta}_v\ (\Delta V)^2}{g\ \Delta lnz\ (\Delta\ \theta\ +\ 0.61\ \overline{\theta}\ \Delta q)}, \tag{37}$$

a solution for the Obukhov length independent of the dimensionless wind shear.

The scaling constants u*, T^*, and q^* are calculated using the discrete forms of equations (11), (12), and (13),

$$u* = \frac{kz\ \Delta V}{\phi_M\ \Delta Z} = \frac{k\ \Delta V}{\phi_M\ \Delta lnZ} \tag{38}$$

$$T^* = \frac{kz\ \Delta\theta}{\phi_M\ \Delta Z} = \frac{k\ \Delta V}{\phi_M\ \Delta lnZ} \tag{39}$$

and

$$q^* = \frac{kz\ \Delta q}{\phi_H\ \Delta Z} = \frac{k\ \Delta q}{\phi_M\ \Delta lnZ}, \tag{40}$$

and while evaluating ϕ_M using equation (14), noting that z = $\Delta z/\Delta$lnz.

6. Discussion

The Mariah approach is simpler than previous solutions involving similarity. Aside from directly estimating the Obukhov scaling length L, Mariah produces results that do not differ numerically from the O'KEYPS equations. Mariah operates using measured gradients, and O'KEYPS operates using chosen trial values and iterating until convergence. Hand calculation using the O'KEYPS equations is tedious.

Figure 1 shows a comparison of scaling specific humidities determined using both schemes. The significant feature is the evaluation of q^* in the stable regime. During the nocturnal hours, evaporation continues to the point before the humidity profiles go isohumic and invert. Inversion of the specific humidity profiles is the first step toward dew fall. The transfer of water vapor from the atmosphere to the surface appears to have little or no effect on the application of dynamic similarity to the surface boundary layer.

Figure 2 shows specific humidity effects on atmospheric stability. An increase of water vapor in the atmosphere in conjunction with larger latent heat fluxes reduces absolute values of the Richardson number or Obukhov scaling length 4 to 10 percent.

Brunner [24] suggests that in the Planetary Boundary Layer relative humidity can be considered a constant in approximately the first 100 m of the atmosphere. Thus, relative humidities calculated from wet and dry bulb temperatures at shelter heights can be easily translated to vapor pressures and specific humidities at tower heights. Although it is not the most exacting method, it will provide the moisture corrections needed for surface energy balance studies.

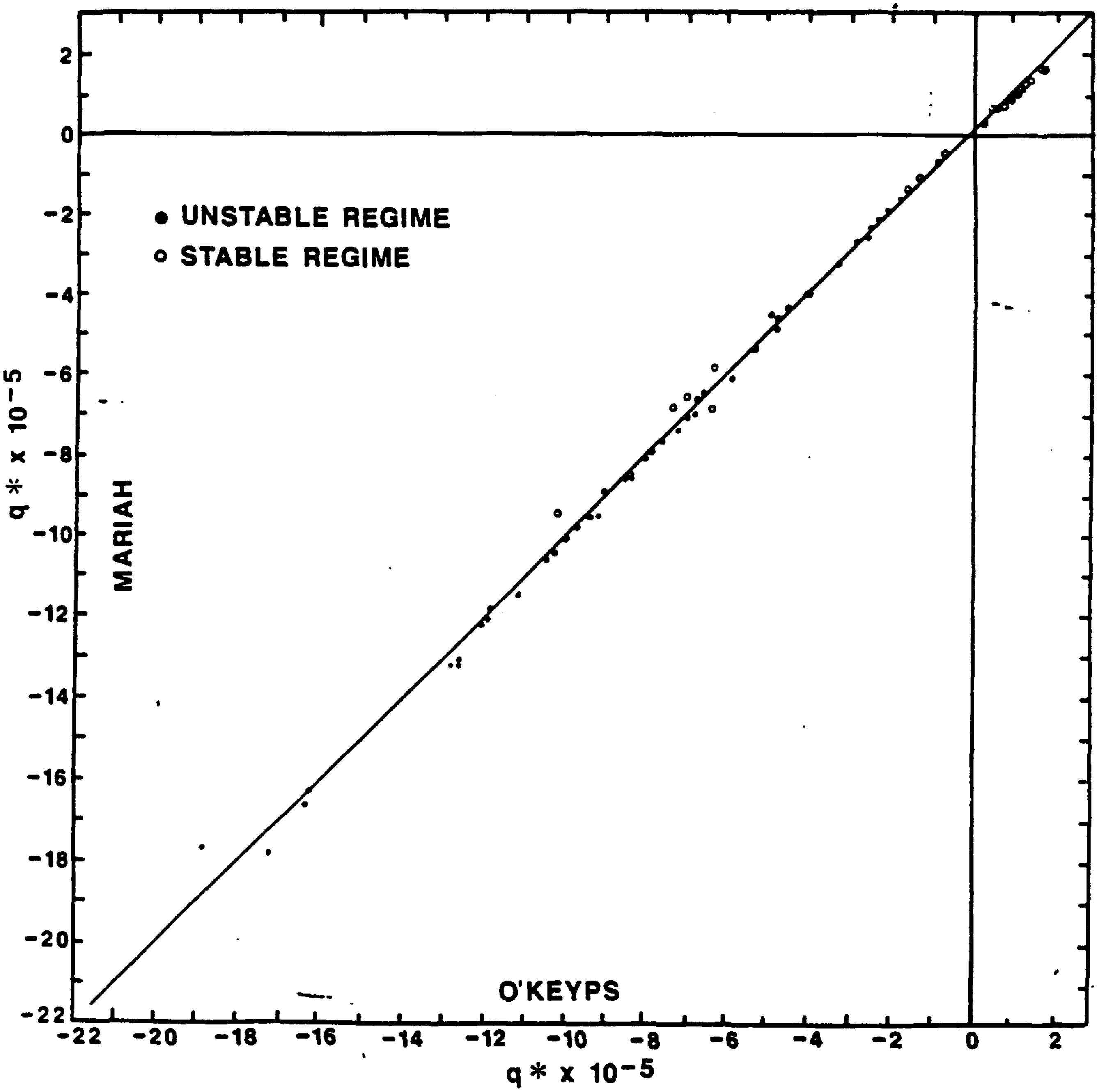

Figure 1. Comparison of scaling specific humidities determined using both schemes.

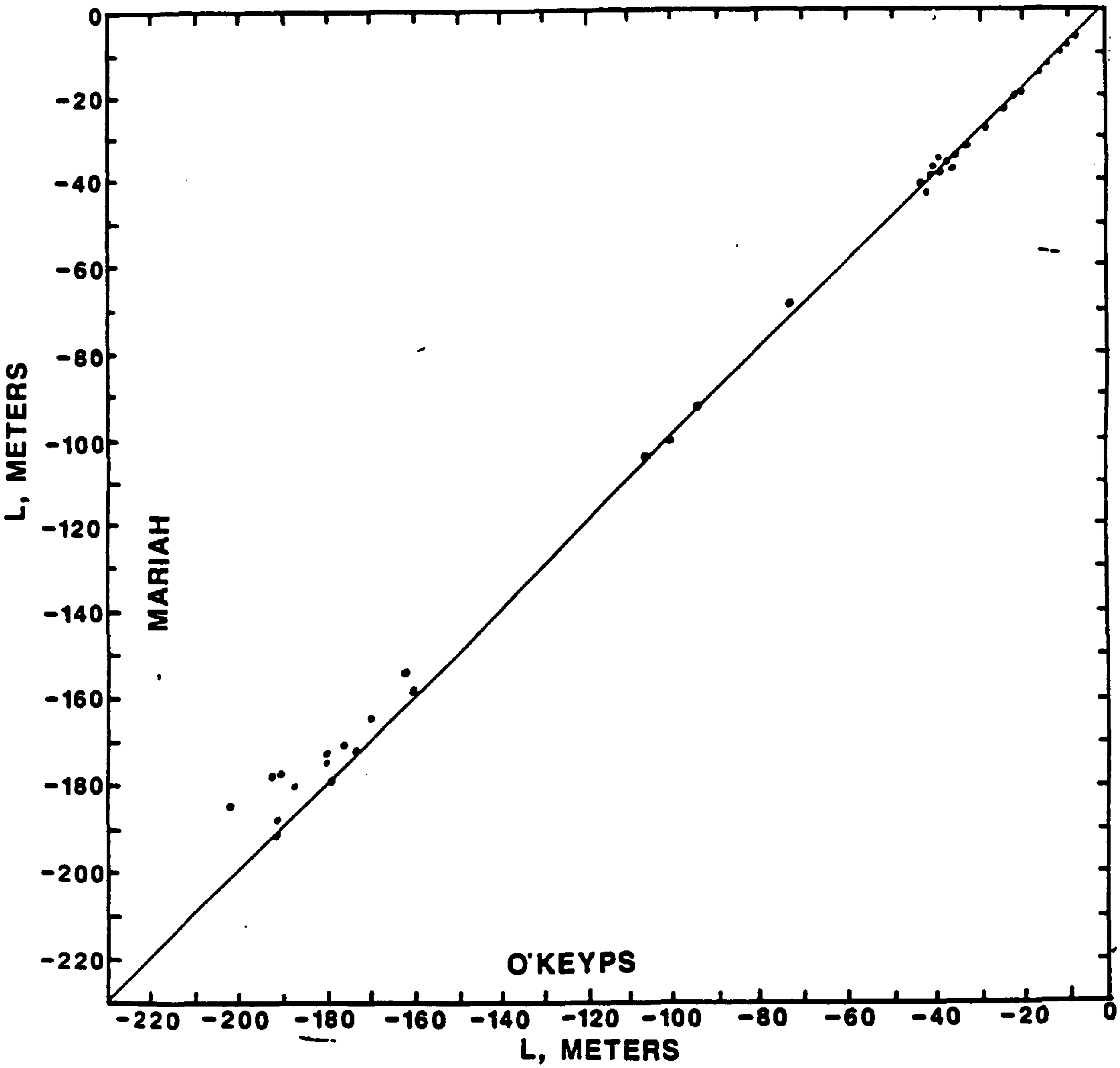

Figure 2. Specific humidity effects on atmospheric stability.

7. Conclusions

The Mariah approach to similarity theory profile analysis is simpler than that of the O'KEYPS methodology, especially if the more formal analyses involving the diabatic influence functions ψ_M (z/L) and ψ_H (z/L) are used to evaluate the scaling parameters u^*, T^*, and q^* in the unstable regime.

O'KEYPS and Mariah appear to function well in the stable regime — especially after inclusion of water vapor in the models. The approach to an isohumic state and the inversion of the specific humidity profiles seems to have little or no effect on the profile analyses schemes, indicating that expansion of the Mariah scheme by estimating specific humidity profiles for shelter height relative humidities is highly feasible for the entire stability spectrum.

References

1. Obukhov, A. M., "Turbulence in an Atmosphere of Nonhomogeneous Temperature," *Trans. Inst. Theor. Geophys. USSR*, 1:95, 1946.

2. Priestly, C. H. B., *Turbulent Transfer in the Lower Atmosphere*, University of Chicago Press, Chicago, IL, 1959.

3. Richardson, L. F., "The Supply of Energy From and to Atmospheric Eddies," *Proc. Roy. Soc. A*, 97:354:373, 1920.

4. Lumley, J. L., and H. A. Panosky, *The Structure of Atmospheric Turbulence*, John Wiley and Sons, New York, NY, pp 239, 1964.

5. Busch, N. E., "On the Mechanics of Atmospheric Turbulence," *Workshop on Micrometeorology* (D. A. Hangen, ed), *Am. Meteorol. Soc.*, Boston, MA, 1973.

6. Monin, A. S., and A. M. Obukhov, "Basic Regularity in Turbulent Mixing in the Surface Layer of the Atmosphere," *Trudy Geophys. Instr. ANSSSR,* 24:163, 1954.

7. Panofsky, H. A., "Determination of Stress From Wind and Temperature Measurements," *Quart J. Roy. Meteorol. Soc.*, 89:85, 1963.

8. Yaglom, A. M., Comments on Wind and Temperature Flux-Profile Relationships. *Boundary Layer Meteorology.*, 11:89-102, 1977.

9. Kazanski, A. B., and A. S. Monin, "Turbulence in the Inversion Layer Near the Surface," *Izv Akard Nauk SSSR*, ser Geofiz, 1:79-86, 1956.

10. Ellison, T. H., "Turbulent Transport of Heat and Momentum from an Infinite Rough Plane," *J. Fluid Mech.*, 2:456, 1957.

11. Yamamota, G., Theory of Turbulent Transfer in Non-Neutral Conditions. *J. Meteorol. Soc. Japan.*, 37:60-70, 1959.

12. Panofsky, H.A., Determination of Stress from Wind and Temperature Measurements. *Quart. J. Roy. Meteorol. Soc.*, 89:85, 1963.

13. Sellers, W. D., A Simplified Derivation of the Diabatic Wind Profile. *J. Atmos. Sci.*, 19:180-181, 1962.

14. Hansen, F. V., *The Critical Richardson Number*. ECOM-5829, U.S. Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM 88002-5501, 1977.

15. Rachele, H., A. Tunick, and F. V. Hansen, *Method for Estimating Similarity Scaling and Obukhov Lengths from Discrete Vertical Profile Data*, TR-0303, U.S. Army Laboratory Command, Atmospheric Sciences Laboratory, White Sands Missile Range, NM, 1991.

16. Businger, J. A. et al., Flux Profile Relationships in the Atmospheric Surface Layer. "*J. Atmos. Sci.*, 18:181-189, 1971.

17. Lettau, H. H., "Computation of Richardson Numbers, Classification of Wind Profiles and Determination of Roughness Parameters," *Exploring the Atmosphere's First Mile*, Vol I, H. H. Letau and B. Davidson, Eds., Pergamon Press, New York, NY, 1957.

18. Webb, E. K., "Profile Relationships: The Log-Linear Range and Extension to Strong Stability," *Quart J. Roy. Meteorol. Soc.*, 96:67-90, 1970.

19. Oke, T. R., "Turbulent Transport Near the Ground in Stable Conditions," *J. Appl. Meteorol.*, 9:778-786, 1970.

20. Hicks, B. B., "Wind Profile Relationships From the Wangara Experiment," *Quart J. Roy. Meteorol. Soc.*, 102:535-551, 1976.

21. Benoit, R., On the Integral of the Surface Layer Profile-Gradient Functions. *J. Appl. Meteorol.*, 16:859-860, 1977.

22. Myrup, L. O., A Numerical Model of the Urban Heat Island, *J. Appl. Meteorol.*, 8:908-918, 1969.

23. Hansen, F. V., *A Technique for Determining Vertical Gradients of Wind and Temperature in the Surface Boundary Layer*, ECOM-5324, U.S. Army Electronic Command, Fort Monmouth, NJ, 1970.

24. Brunner, personal communication, 1975.

Bibliography

Brunner, F. K., "On the Refraction Coefficient of Microwaves," *Bull. Geod.*, 51:257-264, 1977.

Hansen, F. V., *The Critical Richardson Number*, ECOM-5829, U.S. Army Electronic Command, Atmospheric Sciences Laboratory, White Sands Missile Range, NM, 1977.

Sellers, W. D., "A Simplified Deviation of the Diabatic Wind Profile," *J. Atmos. Sci.*, 19:180-181, 1962.

Yaglom, A. M., "Comments on Wind and Temperature Flux-Profile Relationship," *Bound-Layer Meteorol.*, 11:89-102, 1977.

Yamamoto, G., "Theory of Turbulent Transfer in Non-Neutral Conditions," *J. Meteorol. Soc.*, Japan, 37:60-69, 1959.

DISTRIBUTION

	Copies
Commandant U.S. Army Chemical School ATTN: ATZN-CM-CC (Mr. Barnes) Fort McClellan, AL 36205-5020	1
NASA Marshal Space Flight Center Deputy Director Space Science Laboratory Atmospheric Sciences Division ATTN: E501 (Dr. Fichtl) Huntsville, AL 35802	1
NASA/Marshall Space Flight Center Atmospheric Sciences Division ATTN: Code ED-41 Huntsville, AL 35812	1
Deputy Commander U.S. Army Strategic Defense Command ATTN: CSSD-SL-L (Dr. Lilly) P.O. Box 1500 Huntsville, AL 35807-3801	1
Deputy Commander U.S. Army Missile Command ATTN: AMSMI-RD-AC-AD (Dr. Peterson) Redstone Arsenal, AL 35898-5242	1
Commander U.S. Army Missile Command ATTN: AMSMI-RD-DE-SE (Mr. Lill, Jr.) Redstone Arsenal, AL 35898-5245	1
Commander U.S. Army Missile Command ATTN: AMSMI-RD-AS-SS (Mr. Anderson) Redstone Arsenal, AL 35898-5253	1
Commander U.S. Army Missile Command ATTN: AMSMI-RD-AS-SS (Mr. B. Williams) Redstone Arsenal, AL 35898-5253	1
Commander U.S. Army Missile Command Redstone Scientific Information Center ATTN: AMSMI-RD-CS-R/Documents Redstone Arsenal, AL 35898-5241	1

Commander
U.S. Army Aviation Center
ATTN: ATZQ-D-MA (Mr. Heath) 1
Fort Rucker, AL 36362

Commander
U.S. Army Intelligence Center
and Fort Huachuca
ATTN: ATSI-CDC-C (Mr. Colanto) 1
Fort Huachuca, AZ 85613-7000

Northrup Corporation
Electronics Systems Division
ATTN: Dr. Tooley 1
2301 West 120th Street, Box 5032
Hawthorne, CA 90251-5032

Commander
Pacific Missile Test Center
Geophysics Division
ATTN: Code 3250 (Mr. Battalino) 1
Point Mugu, CA 93042-5000

Commander
Code 3331
Naval Weapons Center
ATTN: Dr. Shlanta 1
China Lake, CA 93555

Lockheed Missiles & Space Co., Inc.
Kenneth R. Hardy
ORG/91-01 B/255 1
3251 Hanover Street
Palo Alto, CA 94304-1191

Commander
Naval Ocean Systems Center
ATTN: Code 54 (Dr. Richter) 1
San Diego, CA 92152-5000

Meteorologist in Charge
Kwajalein Missile Range
P.O. Box 67 1
APO San Francisco, CA 96555

U.S. Department of Commerce Center
Mountain Administration
Support Center, Library, R-51
Technical Reports
325 S. Broadway 1
Boulder, CO 80303

Dr. Hans J. Liebe
NTIA/ITS S 3
325 S. Broadway 1
Boulder, CO 80303

NCAR Library Serials
National Center for Atmos Research
P.O. Box 3000 1
Boulder, CO 80307-3000

Headquarters
Department of the Army
ATTN: DAMI-POI 1
Washington, DC 20310-1067

Mil Asst for Env Sci Ofc of
the Undersecretary of Defense
for Rsch & Engr/R&AT/E&LS
Pentagon - Room 3D129 1
Washington, DC 20301-3080

Headquarters
Department of the Army
DEAN-RMD/Dr. Gomez 1
Washington, DC 20314

Director
Division of Atmospheric Science
National Science Foundation
ATTN: Dr. Bierly 1
1800 G. Street, N.W.
Washington, DC 20550

Commander
Space & Naval Warfare System Command
ATTN: PMW-145-1G 1
Washington, DC 20362-5100

Director
Naval Research Laboratory
ATTN: Code 4110
(Mr. Ruhnke) 1
Washington, DC 20375-5000

Commandant
U.S. Army Infantry
ATTN: ATSH-CD-CS-OR (Dr. E. Dutoit) 1
Fort Benning, GA 30905-5090

USAFETAC/DNE 1
Scott AFB, IL 62225

Air Weather Service
Technical Library - FL4414 1
Scott AFB, IL 62225-5458

USAFETAC/DNE
ATTN: Mr. Glauber 1
Scott AFB, IL 62225-5008

Headquarters
AWS/DOO 1
Scott AFB, IL 62225-5008

Commander
U.S. Army Combined Arms Combat
ATTN: ATZL-CAW 1
Fort Leavenworth, KS 66027-5300

Commander
U.S. Army Space Institute
ATTN: ATZI-SI 1
Fort Leavenworth, KS 66027-5300

Commander
U.S. Army Space Institute
ATTN: ATZL-SI-D 1
Fort Leavenworth, KS 66027-7300

Commander
Phillips Lab
ATTN: PL/LYP (Mr. Chisholm) 1
Hanscom AFB, MA 01731-5000

Director
Atmospheric Sciences Division
Geophysics Directorate
Phillips Lab
ATTN: Dr. McClatchey 1
Hanscom AFB, MA 01731-5000

Raytheon Company
Dr. Sonnenschein
Equipment Division
528 Boston Post Road 1
Sudbury, MA 01776
Mail Stop 1K9

Director
U.S. Army Materiel Systems Analysis Activity
ATTN: AMXSY-CR (Mr. Marchetti) 1
Aberdeen Proving Ground, MD 21005-5071

Director U.S. Army Materiel Systems Analysis Activity ATTN: AMXSY-MP (Mr. Cohen) Aberdeen Proving Ground, MD 21005-5071	1
Director U.S. Army Materiel Systems Analysis Activity ATTN: AMXSY-AT (Mr. Campbell) Aberdeen Proving Ground, MD 21005-5071	1
Director U.S. Army Materiel Systems Analysis Activity ATTN: AMXSY-CS (Mr. Bradley) Aberdeen Proving Ground, MD 21005-5071	1
Director ARL Chemical Biology Nuclear Effects Division ATTN: AMSRL-SL-CO Aberdeen Proving Ground, MD 21010-5423	1
Army Research Laboratory ATTN: AMSRL-D 2800 Powder Mill Road Adelphi, MD 20783-1145	1
Army Research Laboratory ATTN: AMSRL-OP-SD-TP Technical Publishing 2800 Powder Mill Road Adelphi, MD 20783-1145	1
Army Research Laboratory ATTN: AMSRL-OP-CI-SD-TL 2800 Powder Mill Road Adelphi, MD 20783-1145	1
Army Research laboratory ATTN: AMSRL-SS-SH (Dr. Sztankay) 2800 Powder Mill Road Adelphi, MD 20783-1145	1
U.S. Army Space Technology and Research Office ATTN: Ms. Brathwaite 5321 Riggs Road Gaithersburg, MD 20882	1

National Security Agency
ATTN: W21 (Dr. Longbothum) 1
9800 Savage Road
Fort George G. Meade, MD 20755-6000

OIC-NAVSWC
Technical Library (Code E-232) 1
Silver Springs, MD 20903-5000

Commander
U.S. Army Research office
ATTN: DRXRO-GS (Dr. Flood) 1
P.O. Box 12211
Research Triangle Park, NC 27009

Dr. Jerry Davis
North Carolina State University
Department of Marine, Earth, and
Atmospheric Sciences 1
P.O. Box 8208
Raleigh, NC 27650-8208

Commander
U.S. Army CECRL
ATTN: CECRL-RG (Dr. Boyne) 1
Hanover, NH 03755-1290

Commanding Officer
U.S. Army ARDEC
ATTN: SMCAR-IMI-I, Bldg 59 1
Dover, NJ 07806-5000

Commander
U.S. Army Satellite Comm Agency
ATTN: DRCPM-SC-3 1
Fort Monmouth, NJ 07703-5303

Commander
U.S. Army Communications-Electronics
Center for EW/RSTA
ATTN: AMSEL-EW-MD 1
Fort Monmouth, NJ 07703-5303

Commander
U.S. Army Communications-Electronics
Center for EW/RSTA
ATTN: AMSEL-EW-D 1
Fort Monmouth, NJ 07703-5303

Commander
U.S. Army Communications-Electronics
Center for EW/RSTA
ATTN: AMSEL-RD-EW-SP 1
Fort Monmouth, NJ 07703-5206

Commander
Department of the Air Force
OL/A 2d Weather Squadron (MAC) 1
Holloman AFB, NM 88330-5000

PL/WE 1
Kirtland AFB, NM 87118-6008

Director
U.S. Army TRADOC Analysis Center
ATTN: ATRC-WSS-R 1
White Sands Missile Range, NM 88002-5502

Director
U.S. Army White Sands Missile Range
Technical Library Branch
ATTN: STEWS-IM-IT 3
White Sands Missile Range, NM 88002

Army Research Laboratory
ATTN: AMSRL-BE (Mr. Veazy) 1
Battlefield Environment Directorate
White Sands Missile Range, NM 88002-5501

Army Research Laboratory
ATTN: AMSRL-BE-A (Mr. Rubio) 1
Battlefield Environment Directorate
White Sands Missile Range, NM 88002-5501

Army Research Laboratory
ATTN: AMSRL-BE-M (Dr. Niles) 1
Battlefield Environment Directorate
White Sands Missile Range, NM 88002-5501

Army Research Laboratory
ATTN: AMSRL-BE-W (Dr. Seagraves) 1
Battlefield Environment Directorate
White Sands Missile Range, NM 88002-5501

USAF Rome Laboratory Technical
Library, FL2810 1
Corridor W, STE 262, RL/SUL
26 Electronics Parkway, Bldg 106
Griffiss AFB, NY 13441-4514

AFMC/DOW 1
Wright-Patterson AFB, OH 03340-5000

Commandant
U.S. Army Field Artillery School
ATTN: ATSF-TSM-TA (Mr. Taylor) 1
Fort Sill, OK 73503-5600

Commander
U.S. Army Field Artillery School
ATTN: ATSF-F-FD (Mr. Gullion) 1
Fort Sill, OK 73503-5600

Commander
Naval Air Development Center
ATTN: Al Salik (Code 5012) 1
Warminister, PA 18974

Commander
U.S. Army Dugway Proving Ground
ATTN: STEDP-MT-M (Mr. Bowers) 1
Dugway, UT 84022-5000

Commander
U.S. Army Dugway Proving Ground
ATTN: STEDP-MT-DA-L 1
Dugway, UT 84022-5000

Defense Technical Information Center
ATTN: DTIC-OCP 2
Cameron Station
Alexandria, VA 22314-6145

Commander
U.S. Army OEC
ATTN: CSTE-EFS 1
Park Center IV
4501 Ford Ave
Alexandria, VA 22302-1458

Commanding Officer
U.S. Army Foreign Science & Technology Center
ATTN: CM 1
220 7th Street, NE
Charlottesville, VA 22901-5396

Naval Surface Weapons Center
Code G63 1
Dahlgren, VA 22448-5000

Commander and Director
U.S. Army Corps of Engineers
Engineer Topographics Laboratory
ATTN: ETL-GS-LB 1
Fort Belvoir, VA 22060

U.S. Army Topo Engineering Center ATTN: CETEC-ZC Fort Belvoir, VA 22060-5546	1
Commander USATRADOC ATTN: ATCD-FA Fort Monroe, VA 23651-5170	1
TAC/DOWP Langley AFB, VA 23665-5524	1
Commander Logistics Center ATTN: ATCL-CE Fort Lee, VA 23801-6000	1
Science and Technology 101 Research Drive Hampton, VA 23666-1340	1
Commander U.S. Army Nuclear and Chemical Agency ATTN: MONA-ZB, Bldg 2073 Springfield, VA 22150-3198	1
Record Copy	3
Total	89